

THERMAL ANALYSIS OF COMPOUND PARABOLIC CONCENTRATOR

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ABSTRACT

A mathematical model is constructed by using the thermal properties and thermal mathematical equations. For a particular geometry of a compound parabolic concentrator such as acceptance angle 30° , concentration ratio 2, length 1.6 meter, the thermal efficiency and performance is calculated by using the mathematical model. The solar radiation fall on the compound parabolic concentrator is also calculated. The thermal performance, efficiency and solar radiation is calculated for Patan, Gujarat, India (23.4°N , 72°E). The effects of air mass flow rate, Wind Velocity and solar radiation on the thermal performance of compound parabolic concentrator is calculated theoretically which is close agreement with experimental data that indicate thermal efficiency increase as mass flow rate increase and gain in temperature decreases. As wind velocity increases, the overall loss coefficient increases so that thermal efficiency decreases.

KEYWORDS: Compound Parabolic Concentrator (CPC), Flat Receiver, Parabolic Reflector, Thermal Analysis, Efficiency

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INTRODUCTION

Compound parabolic concentrator is non-focusing type concentrating collector and provides moderately solar radiation concentration although less than a focusing collector it does not require continuous tracking of the sun but it need necessities only a few tilt adjustment per year. The concentration ratio (C) is the ratio of area of aperture to the area of receiver, which is generally ranging from 2 to 9. The acceptance angle is denoted by Θ_a and calculated as $C = \frac{1}{\sin \Theta_a}$. As having higher acceptance angle the efficiency of accepting diffuse radiation is much larger than the conventional concentrators. Compound parabolic concentrator consists of two parabolic reflector, glass cover, flat plate absorber as shown in figure [1]. Rays in the central region of the aperture reach the absorber directly where as those near edges undergo one or more reflection before reaching the absorber. Reflector is selected in such a way that it reflects the ray at high rate. Reflector should not consist higher absorptivity. In opposite receiver is selected in such a way that it have higher absorptivity and lower reflectivity. It also consists higher thermal conductivity so that it transfers heat to the fluid at high rate. Most receiver material does not have high absorptivity so they need to be covered with special solar selective surface coatings. The rays inside the CPC have lower wave length so there are possibilities of loss of these infrared rays. The glass cover does not allow to these rays to go outside, so it reduces the loss and also protects CPC from dust and other particles. The properties of air are shown in table 1. The characteristics of CPC are shown in table 2[15]. The schematic fig of compound parabolic concentrator is shown in figure 1.

REVIEW OF LITERATURE

A solar air heater which heats the air by solar energy it have many application in drying agricultural products such as seeds [1], fruits and vegetables [2-3]. Solar air-heaters are utilised for heating buildings with auxiliary heaters to save energy in winter-time [4]. Garg *et al.* [5] concluded that the multiple-pass air heater performs well for low flow rates and large plate lengths.

Wijaysundera *et al.* [6] perform experiments and concluded that in two pass mode (inlet air flows first above the receiver plate then under it.) increase efficiency up to 10-15%. Ezeike [7] concluded that the a triple pass flat collector gives the average efficiency of 70-80% with air velocity up to 3.5 m/s. Yeh *et al.* [8] and El-sebily *et al.* [9] designed double flow solar air heater with fins attached over and under the absorbing plate. Tchinda and Ngos [10] developed equation for calculating thermal performance of CPC collector with a flat side receiver, with various dimensions and concluded that efficiency increase as mass flow rate increase and gain in temperature decreases.

METHODOLOGY

Calculation of Solar Radiation

Solar radiation can be found by calculating the beam radiation and diffuse radiation. These radiations can found by [11].

Calculation of Diffuse Radiation

The diffuse radiation can be found by [13]

$$I_{DN} = A_1 \times \exp\left(-\frac{P_L}{P_0} \times \frac{B}{\sin \alpha}\right)$$

Where P_L/P_0 is the pressure ratio at location concentrated relative to the standard atmospheric pressure given as

$$\frac{P_L}{P_0} = \exp(-0.0001184 \times H_{alt})$$

Where H_{alt} is altitude in (m) from sea surface.

The extra-terrestrial solar intensity A_1 , the atmospheric extinction coefficient B , and sky-diffused factor, C_1 , were calculated by Joudi (1988) [12] for any day by the following equations:

$$A_1 = 1158 \times \left(1 + 0.066 \times \cos\left(360 \times \frac{ND}{370}\right)\right)$$

$$B = 0.175 \times [(1 - 0.2 \times \cos(0.93 \times ND)) - 0.0045 \times [1 - \cos(1.86 \times ND)]]$$

$$C_1 = 0.0965 \times \left[1 - 0.42 \times \cos\left(\frac{360}{370} \times ND\right)\right] - 0.0075 \times [1 - \cos(1.95 \times ND)]$$

Where, ND=number of day in year.

The sun altitude angle α is given by (Lunde, 1980) [13] as:

$$\alpha = \sin^{-1}(\cos \phi \times \cos \delta \times \cos w + \sin \delta \times \sin \phi)$$

The declination angle

$$\delta = 23.45 \sin\left(\frac{360}{365} \times (285 + ND)\right)$$

Where,

ϕ = latitude angle (for Patan $\phi = 23.8667$)

w = the hour angle, this angle is expressed in degree as:

$$w = 15 \times (\text{solar time} - 12)$$

Where the solar time calculated as:

$$\text{Solar time} = \text{standard time} + (E/60) - ((L_{\text{st}} - L_{\text{local}})/15)$$

Where,

E = correction time which is in hour, which is taken as 0.020833

L_{st} = standard meridian for local time zone (for india it is 82.5^0)

L_{local} = longitude of the location in degree (for patan it is 72.0167^0)

Calculation of Beam Radiation

The beam radiation is given by

$$I_B = I_{DN} \times \cos \theta_1$$

Where, $\cos \theta_1$ is calculated by [14] :

$$\cos \theta_1 = [(\sin \delta \times \sin \phi \times \cos \beta) - (\sin \delta \times \cos \phi \times \sin \beta \times \cos \gamma) + (\cos \delta \times \cos \beta \times \cos \phi \times \cos \omega) + (\cos \delta \times \sin \phi \times \sin \beta \times \cos \gamma \times \cos \omega) + (\cos \delta \times \sin \beta \times \sin \gamma \times \sin \omega)]$$

Where

γ = surface azimuth angle, it is on horizontal plane between the line due south and the horizontal projection on the normal to the inclined plane surface.

β = slop of the collector (23^0 for summer and 46^0 for winter)

The diffuse radiation on tilted collector is given (Lunde, 1980) [13] as:

$$I_D = I_{DN} \times \left[(C_1 \times (1 + \cos \beta)/2) + (S \times (C_1 + \sin \alpha) \times \left(\frac{1 - \cos \beta}{2} \right)) \right]$$

Where

S = ground reflectivity, which is 0.2

Total Solar Radiation

The total solar radiation is calculated by

$$I_T = I_D + I_B$$

Calculation of Overall Loss Coefficient

Compound parabolic concentrator consists various heat losses. The wind velocity also affects the performance of the CPC. If the velocity is higher, then the loss is increased and so that lower efficiency is obtained.

Calculation of Wind Heat Transfer Coefficient (h_w):

The convective heat loss coefficient can calculate by Duffie and Beckman [14] as:

$$\text{Reynold number} = \frac{\rho_{\text{air}} v_{\text{air}} D_h}{\mu_{\text{air}}}$$

Where,

ρ_{air} = Density of air, kg/m³

μ_{air} = Dynamic viscosity of air, Ns/m²

v_{air} = velocity of wind, m/s

$$D_h = \left(\frac{2w_a \times h}{w_a + h} \right)$$

Where, w_a = width of aperture

h = height of compound parabolic concentrator

Nusselt number:

$$\text{Nu} = 0.40 + 0.54 \text{Re}^{0.52} \text{ for } 0.1 < \text{Re} < 1000$$

$$= 0.30 \times \text{Re}^{0.6} \text{ for } 1000 < \text{Re} < 50000$$

$$\text{Nusselt number} = (h_w \times \frac{D_h}{k_{\text{air}}})$$

Where,

h_w = wind loss

k_{air} = thermal conductivity of air

The heat loss is calculated in two parts. The heat loss and overall loss coefficient are calculated by Duffie and Beckman [14]:

Heat loss From Absorber Plate to Cover Plate

- Conduction loss

- Radiation loss

Heat Loss from Cover Plate to Sky

- Convection loss due to wind
- Radiation loss

Conductive Heat Loss from the Receiver Surface to Cover Plate

$$Q_{COND} = K_{AIR} \times A_R \times (T_R - T_C)$$

Radiation Heat Loss from Receiver Surface to Cover Plate

$$Q_{RAD1} = \frac{A_R \times \sigma \times (T_R^4 - T_C^4)}{(\frac{1}{\epsilon_R} + \frac{1}{\epsilon_C} - 1)}$$

Convective Heat Loss from Cover Plate to Air

$$Q_{CONV} = A_C \times h_w \times (T_C - T_A)$$

Radiation Heat Loss from Cover Plate to Sky

$$Q_{RAD2} = A_C \times \sigma \times (T_C^4 - T_{SKY}^4)$$

Overall Loss

$$Q_{LOSS} = Q_{COND} + Q_{RAD1} + Q_{CONV} + Q_{RAD2}$$

Overall Loss Coefficient

$$U_L = \frac{Q_{LOSS}}{A_R \times (T_R - T_I)}$$

Thermal Efficiency

The thermal efficiency depends on various factors such as overall loss coefficient (U_L), solar radiation (I), aperture area (A_a), receiver area (A_R). The thermal efficiency is calculated by Duffie and Beckman [14] as:

$$Q_U = F_R \times A'_R \times (H - \frac{A_R}{A'_R} \times U_L \times (T_I - T_R))$$

Where,

H = solar radiation \times reflectivity of reflector \times absorptivity of absorber

A'_R = Area of aperture without shading

T_I, T_A, T_R = Inlet, Ambient, Receiver temperature respectively

$$F_R = F' \times F''$$

$$F' = \frac{U_0}{U_L}$$

$$F'' = \frac{m \times C_p}{A_R U_L F'} \left[1 - \exp\left(-\frac{A_R U_L F'}{m \times C_p}\right) \right]$$

Rise in Temperature

$$\Delta T = \frac{Q_U}{m \times C_p}$$

Outlet Temperature

$$T_0 = T_i + \Delta T$$

Efficiency

$$\eta = \frac{Q_U}{I \times A_a}$$

RESULTS AND DISCUSSION

Figure 2 shows Time vs. solar radiation, it shows that solar radiation is change throughout the year. It is maximum in March to June and minimum in September to December. Fig 3 shows wind velocity vs. overall loss coefficient, it is concluded that as wind velocity is higher, then loss of heat is at high rate, which reduces the thermal efficiency. Figure 4 Shows Day time vs. Temp, it is concluded that outlet temp is maximum at noon and minimum at morning. Figure 5 shows the outlet temperature vs length for different mass flow rate.it shows that the outlet temperature is higher as length increases. it also shows that at mass flow rate $m=0.012$ kg/s higher outlet temperature is obtained.

Figure 6 shows mass flow vs outlet temperature for different length $L=1.6, 2, 2.2$ meter. It shows as mass flow rate increase the outlet temprature decreases. Figure 7 shows mass flow vs. efficiency for different velocity 1m/s and 8m/s. it shows that due to higher velocity heat loss is higher, so that at higher velocity the efficiency is lower. And thermal efficiency increases as mass flow increases. Figure 8 shows Day time vs. Efficiency, it is concluded that efficiency is also varies with time, which is higher at noon and lower at morning.

CONCLUSIONS

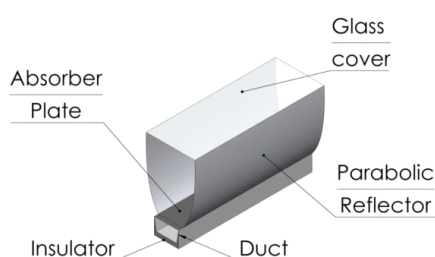
As we increase the mass flow rate, outlet temperature decreases and thermal efficiency increases. As wind velocity increases, the overall heat loss increases, which reduces rise in outlet temperature so that efficiency also decreases. This method is useful to calculating the effect of mass flow rate, wind velocity on thermal efficiency of Compound parabolic concentrator.

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APPENDICES



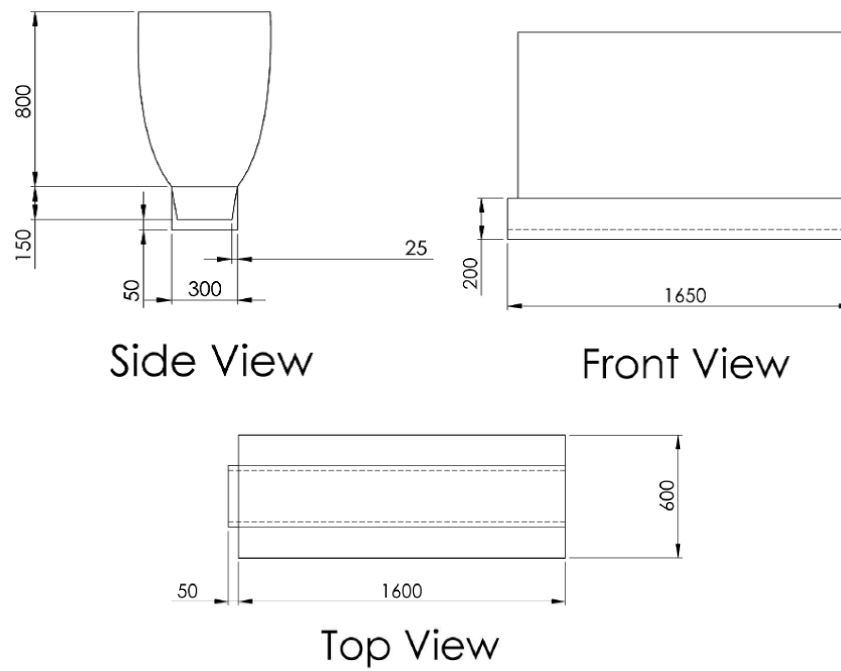


Figure 1: Schematic View of Compound Parabolic Concentrator

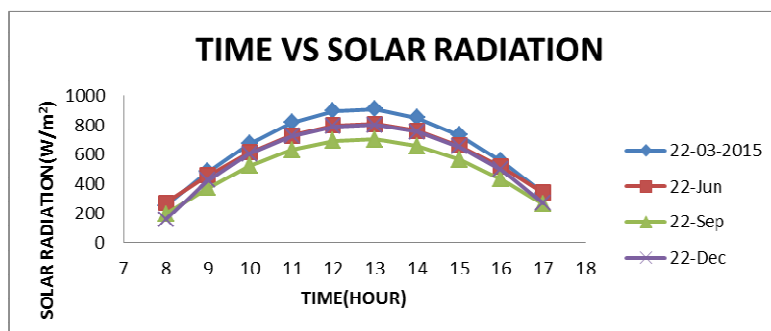


Figure 2: Time vs. Solar Radiation

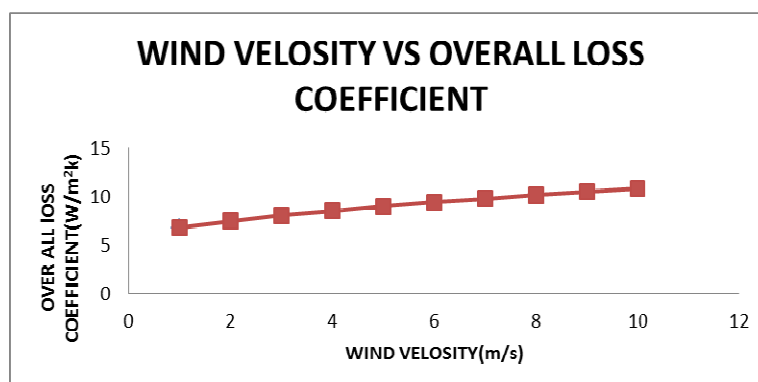


Figure 3: Wind Velocity vs. Overall Loss Coefficient

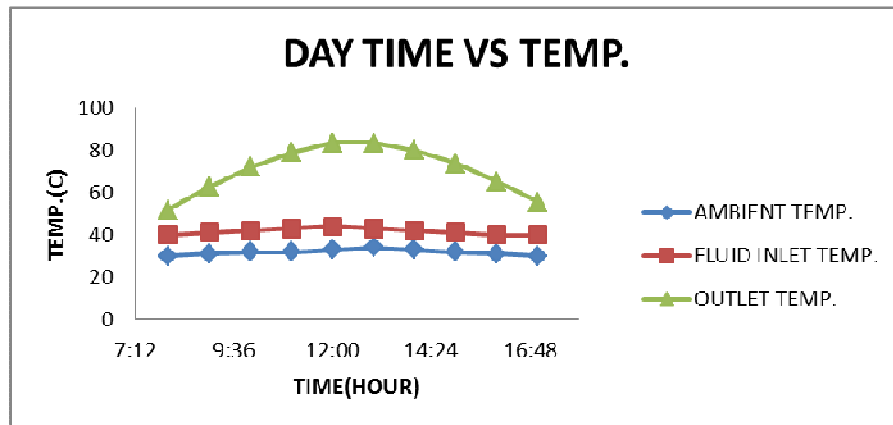
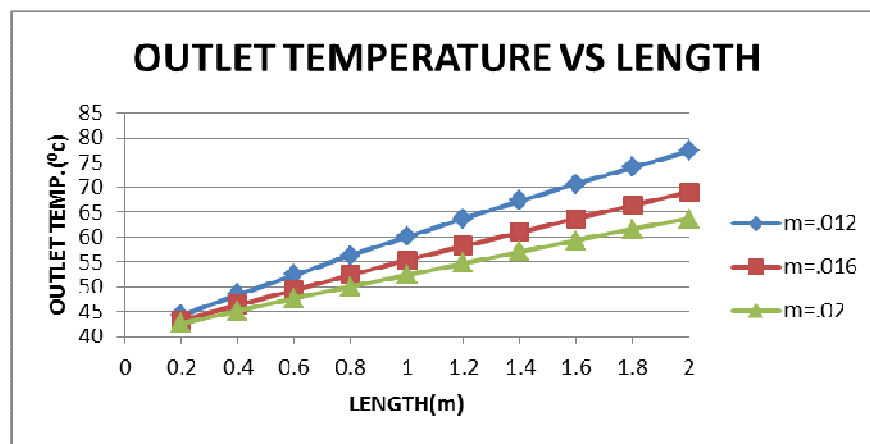
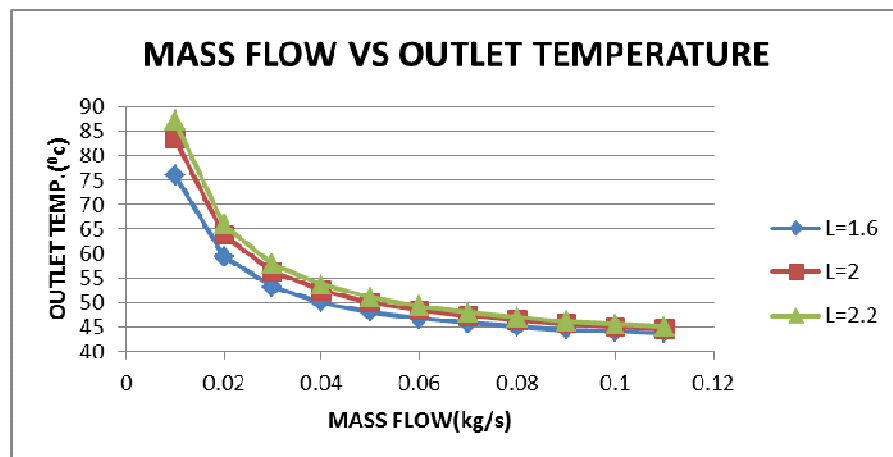


Figure 4: Day Time vs. Temperature

Figure 5: Outlet Temperature vs Length (for Mass Flow Rate $m=0.02, 0.016, 0.012$ kg/s)Figure 6: Mass Flow vs Outlet Temp.(for Length $L=1.6, 2, 2.2$ meter)

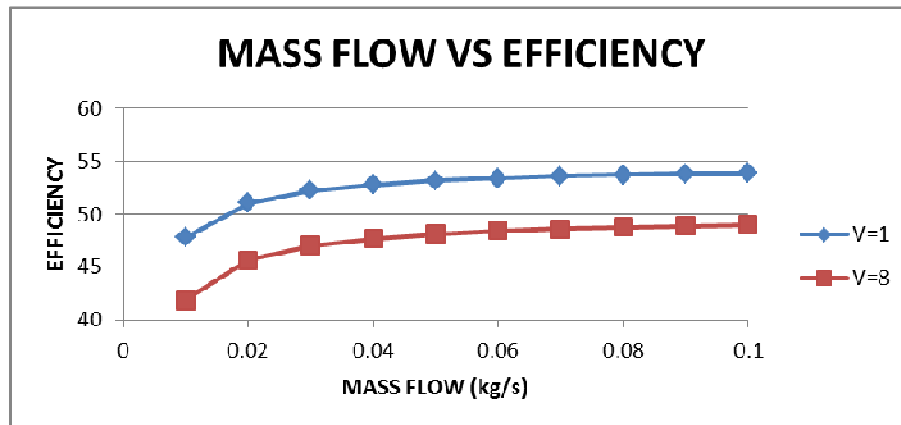


Figure 7: Mass Flow vs. Efficiency (velocity v=1, 8 m/s)

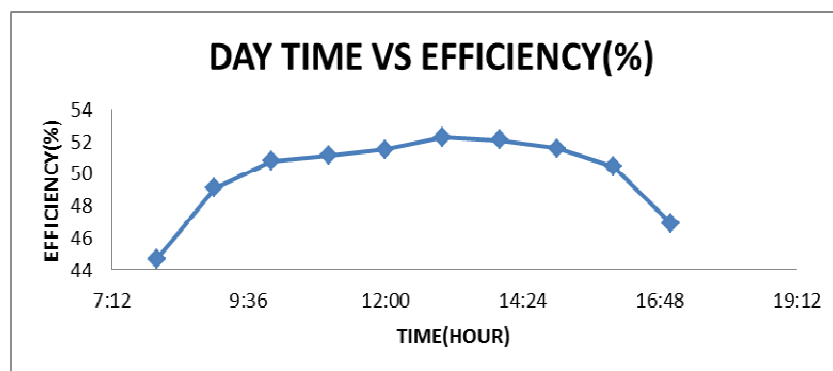


Figure 8: Day Time vs. Efficiency

Table 1: Properties of Air

Parameter	Unit	Value
Density	Kg/m ³	1.127
Dynamic viscosity	Ns/m ²	0.00001983
Thermal conductivity	W/mk	0.0271

Table 2: Characteristics of Compound Parabolic Collector

Parameter	Unit	Value
Cover absorptance	-	0.05
flat plate absorber absorptance	-	0.95
Cover transmittance	-	0.89
Cover emittance	-	0.85
Flat plate absorber emittance	-	0.31
Cover reflectance	-	0.05
Reflector reflectance	-	0.86
Flat plate absorber reflectance	-	0.15